

Combined tensiometer–solution sampling probe

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Abstract

Variables needed to characterize solute transport in soils are soil water pressure (SWP) and solute concentration, which are typically obtained from tensiometers and suction solution samplers, respectively. In this paper we describe a combined tension–solution sampling probe that measures SWP, and allows extraction of soil solution during or between SWP measurements. A separate porous ceramic cup and ring to be used for the tensiometer and suction solution sampler were built into a single unit. Laboratory soil column experiments were carried out to evaluate the performance of the combined tension–solution probe, and the data obtained were compared with those from using separate tensiometer and suction solution samplers. Differences in tensiometric measurements were attributed to differences in size between the tensiometers. An apparent increase in pore water solution concentration as soil water potential is decreased could be explained by anion exclusion. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Contamination of the subsurface due to point and nonpoint sources of pollution remains one of the most perplexing environmental issues of our time. There is growing awareness that gradual but pervasive deterioration of groundwater quality occurs by both point and nonpoint sources of contamination from agricultural and urban land uses. However, cause and effect relationships between these land uses and subsurface water quality remain partly an enigma.

For solutes to reach the groundwater, they must pass through the unsaturated soil or vadose region. Transport prediction requires accurate characterization of the soil and soil

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water environment, including hydraulic properties. The measurement of representative soil water pressure and soil solution concentrations are fundamental tasks for the vadose zone hydrologist. The requirement for adherence to reproducible sample and data collection protocol is well known and understood by the increasing use and sophistication of numerical models. Interpretation of results can only be as meaningful as the manner in which the basic field data or samples are collected.

A sensor that allows measurement of soil water pressure (SWP) and the sampling of soil water concurrently is proposed. The soil water energy status or SWP can be measured by tensiometers (Gardner et al., 1922; Richards and Gardner, 1936; Richards, 1949). The technique of soil solution extraction utilizing porous ceramic cups was first described by Briggs and McCall (1904). Since then, ceramic solution cups are traditionally used for the sampling of soil solution in the plant root zone (Nielsen, 1976). Various porous ceramic cup solution sampler designs have been described over the years, such as porous tube device, vacuum extractor, tension and suction lysimeter, soil water sampler, and porous ceramic sampler.

The use of suction solution samplers has increased with the introduction of new designs (Wagner, 1962; Linden, 1977). Modifications to the original designs continued as limitations were discovered. Cole (1968) introduced an automated suction solution sampler with multiple samplers connected to a vacuum tank and electrical source. Wood (1973) developed a suction solution sampler capable of collecting samples from depths greater than 10 m. Harris and Hansen (1975) described a miniature suction solution sampler eliminating sample transfers in the field. Chow (1977) designed a suction solution sampler that automatically shuts off when the desired sampling volume is collected. The device of Knighton and Streblov (1981) prevented reverse flow of collected soil solution during sampling under drying soil conditions. Suarez (1986) described a suction solution sampler that reduces the degassing of CO₂ and pH effects on solution sampling. Hubbell and Sisson (1996) described the application of a portable tensiometer design that combines a porous cup, a water reservoir sealed with a rubber septum, and a pressure transducer into a single module. The combined unit can be lowered in a borehole to monitor soil water pressures at large depths. An excellent review of types and operation of soil solution samplers is presented by Litaor (1988).

Although there is an increasing need for improved in situ soil solution samplers, developments in this area are rather scarce. Recent attempts have been made to develop a single device capable of measuring multiple soil characteristics. For example, Morrison and Szecsody (1987) presented a design, which can be used as either a tensiometer or soil water sampler. The sampling probe included an automated refilling system to eliminate gas accumulation in tensiometric measurements, and a pressure transducer within the probe that allows tensiometer readings in excess of 10 m depth. Tokunaga (1992) discusses the possibility for simultaneous soil solution sampling and tensiometry, by which soil water pressure is inferred by changes in pressure and sample volume in the soil solution sampler. Moutonnet et al. (1993) presented a combined soil nitrate concentration and soil water pressure sensor that measures the concentration of the tensiometer solution by diffusion of soil solutes into the tensiometer via the porous cup. Furthermore, Baumgartner et al. (1994) designed a time domain reflectometry probe capable of measuring water content and SWP, and the sampling of soil solution.

The objective of this investigation was to develop a simple single probe which allows soil solution sampling during or between soil water pressure measurements. The proposed segmented tensiometer–solution sampling probe minimizes soil disturbance by integrating the two units into a single probe. Admittedly, at the time of the design and testing of the combined probe, we overlooked the study by Starr et al. (1986). Their multiple tensiometer-sampler (MTS) is similar in capabilities but was specifically designed for tensiometric measurements and soil solution sampling at multiple soil depths. Each of the five 2-cm long porous ceramic rings could be used for either tensiometry or solution sampling. Probe sections were held together by a stainless steel rod fitted through each section. We report on the design and operation of an easy-to-assemble unit consisting of two compartments, with the objective to measure soil water pressure at a single depth only, and which can be used simultaneously for soil water sampling near the tensiometric measurement location.

2. Materials and methods

2.1. Probe construction

Conventional tensiometers and soil solution samplers are very similar in design, and consist of a porous ceramic cup glued into a PVC pipe. Marthaler et al. (1983) described the portable digital readout pressure transducer which measures the SWP, when attached to the tensiometer through a rubber septum (Soil Measurement Systems, Tucson, AZ).¹ The tensiometer is filled with water, installed into the soil to the desired depth, and SWP is monitored using a pressure transducer after pressure equilibration. Simply by extending sampling tubing from the porous cup chamber to a sampling bottle, the same design is used as a soil solution sampling probe. After soil installation, a sample bottle is attached to the sampling tube and vacuum is applied to the solution sampler. Sampling duration depends on soil type, SWP, applied vacuum, and required sample volume. Simultaneous measurement of SWP and soil solution extraction either requires installation of two separate probes, or repeated filling and draining of the tensiometer housing.

Construction of the proposed combined tension-solution probe requires two separate porous ceramic compartments within a 2.2 cm OD PVC pipe, of variable length. For the design in Fig. 1, a 5.4 cm long porous 2.2 cm OD ceramic cup (Soilmoisture Equip., Santa Barbara, CA, model #655) was cut in half. The two compartments of the porous ceramic cup were separated by an acrylic barrier in which two holes were drilled to accommodate small diameter tubing. Two holes were drilled near the top end of the PVC pipe. The small diameter tubing is guided through the holes at the top of the PVC pipe and through the acrylic barrier into the bottom compartment of the probe. One tube feeds just through the barrier, while the other tube extends to the bottom of the porous ceramic cup. The longer sampling tube at the base of the ceramic cup is used for the

¹ Mention of brand names is solely for the convenience of the reader and implies no endorsement by the authors or their institution.

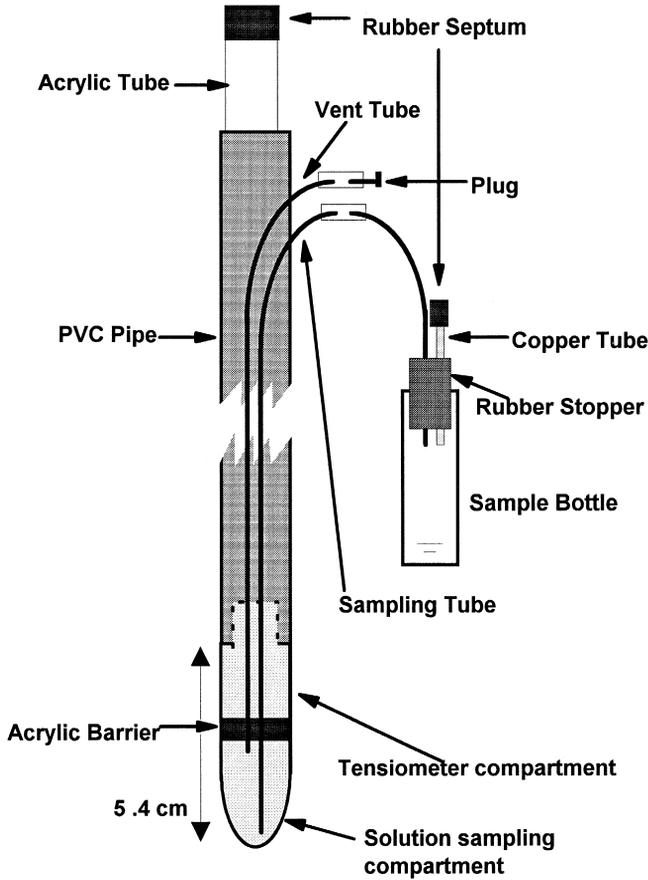


Fig. 1. Design of combined tension–soil solution probe.

transfer of soil solution from the ceramic cup to the sample bottle by vacuum application. The shorter vent tube near the acrylic barrier allows air entry into the solution sampling compartment as it is emptied. Also, a positive pressure can be applied to the vent tube, thereby assisting in the transfer of solution from the sampling compartment to the sample bottle aboveground. The two-compartment ceramic cup assembly was cemented to the bottom of the PVC pipe. Devcon 2-Ton Clear Epoxy¹ (Devcon Consumer Products, Wood Dale, IL 60191) was used to cement all components of the tension-solution sampling probe together. A short piece of 1.6 cm OD acrylic tubing was cemented into the top of the tensiometer compartment, and closed with a rubber septum. Soil water pressure was measured by the approach of Marthaler et al. (1983). Thus, the combined probe consists of two separate compartments, with the top compartment acting as a tensiometer, whereas the bottom chamber serves as the soil water extraction device.

After soil installation, a sample bottle is attached to the longer sampling tubing. The sampling tubing from the rubber stopper assembly (Fig. 1) and the probe are coupled using a small piece of Norprene¹ tubing size 14 (Cole Parmer Instrument, Niles, IL). Vacuum to the sample bottle and soil solution sampling compartment of the combined probe was applied by a hand pump. The tensiometer portion of the probe was filled with deionized water to within several centimeters of the top of the acrylic tube.

2.2. Laboratory evaluation

Column experiments were carried out to evaluate the performance of the combined tensiometer–solution sampling probe and to compare data with those collected with conventional tensiometers and suction solution samplers.

The experiment consisted of three columns packed with Hanford sandy loam (coarse-loamy, mixed, nonacid, thermic Typic Xerorthent), Panoche loam (fine-loamy,

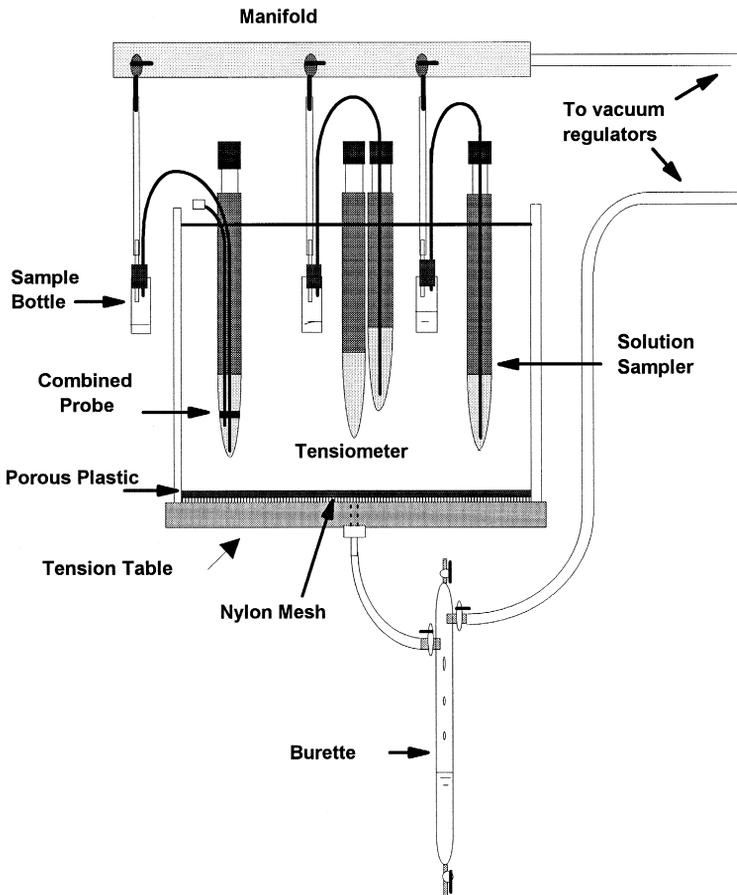


Fig. 2. Instrumented soil column mounted on tension table.

mixed (calcareous), thermic Typic Torriorthent) and Yolo silt loam (fine-silty, mixed, nonacid, thermic Typic Xerorthent). Soils were leached with a saturated solution of calcium sulfate, which reduced background chloride concentrations to 1.56 (Yolo), 3.09 (Panoche), and 1.20 meq l⁻¹ (Hanford). The calcium sulfate solution was also used to prevent dispersion of soil aggregates. Subsequently, all soils were air-dried, sieved through a 2-mm screen, and packed to a depth of 11.0 cm in 20.7 cm diameter columns. Bulk densities for the Hanford sandy loam, Panoche loam and Yolo silt loam were 1.78 g cm⁻³, 1.33 g cm⁻³ and 1.34 g cm⁻³, respectively.

The soil columns were subsequently saturated with a 97.0 meq l⁻¹ CaCl₂ (stock solution) by immersion in a solution bath and were placed on a tension table (Fig. 2). The tension table included porous plastic (grade A-20) with a bubbling pressure of approximately 620 cm water (FMC¹, Pine Brook, NJ) and a nylon mesh. Vacuum was applied to a burette, which was connected to the tension table with tygon tubing. Each column was instrumented with two conventional suction solution samplers, one conventional tensiometer, and a single combined tensiometer-solution sampling probe. The lower end of all samplers was installed at 3.1 cm from the bottom of the column. The conventional tensiometer was centered in each column, whereas the two conventional suction solution samplers and the combined probe were placed at equal distances of 5.5 cm from the center in a circular pattern.

The soils were covered with plastic to prevent evaporation. The columns were drained by applying suction (expressed in equivalent height of water) steps of 30 cm, 100 cm, 200 cm, 300 cm and 400 cm to the burette. Changes in SWP were monitored with the tensiometers and the combined probes. Soil solution was extracted after the measured SWP was equal to the suction applied to the soil columns. The constant vacuum applied for soil solution extraction was 50 cm greater than the applied suction step to the columns at all times. Vacuum for soil solution extraction and applied suction steps to porous plastic membrane were controlled separately. Soil solution extractions were analyzed for chloride concentration using a 4-4415 Clinical Chloride Titrator (American Instrument¹, Silver Spring, MD). The chloride titrator was calibrated using a standard curve using CaCl₂ solutions in the range from 25 to 125 meq l⁻¹. Using replicates of standard solutions, instrument accuracy was approximately 2.0 meq l⁻¹.

3. Results

3.1. Soil water pressure

Values of SWP (expressed in equivalent height of water, cm) as measured with the tensiometer and combined tension-solution sampling probe are presented in Fig. 3a combined with cumulative drainage (ml) as a function of time for the Yolo soil. As an example, changes in SWP during the 200-cm suction increment are labeled by points A through D in Fig. 3a. Point A (about 100 h) is the time that the soil is at hydraulic equilibrium with the 100-cm suction increment, and indicates the beginning of the drainage period with 200 cm suction applied to the porous membrane. At the time of Point B, the equilibrium SWP of -200 cm has been reached, after which soil solution is

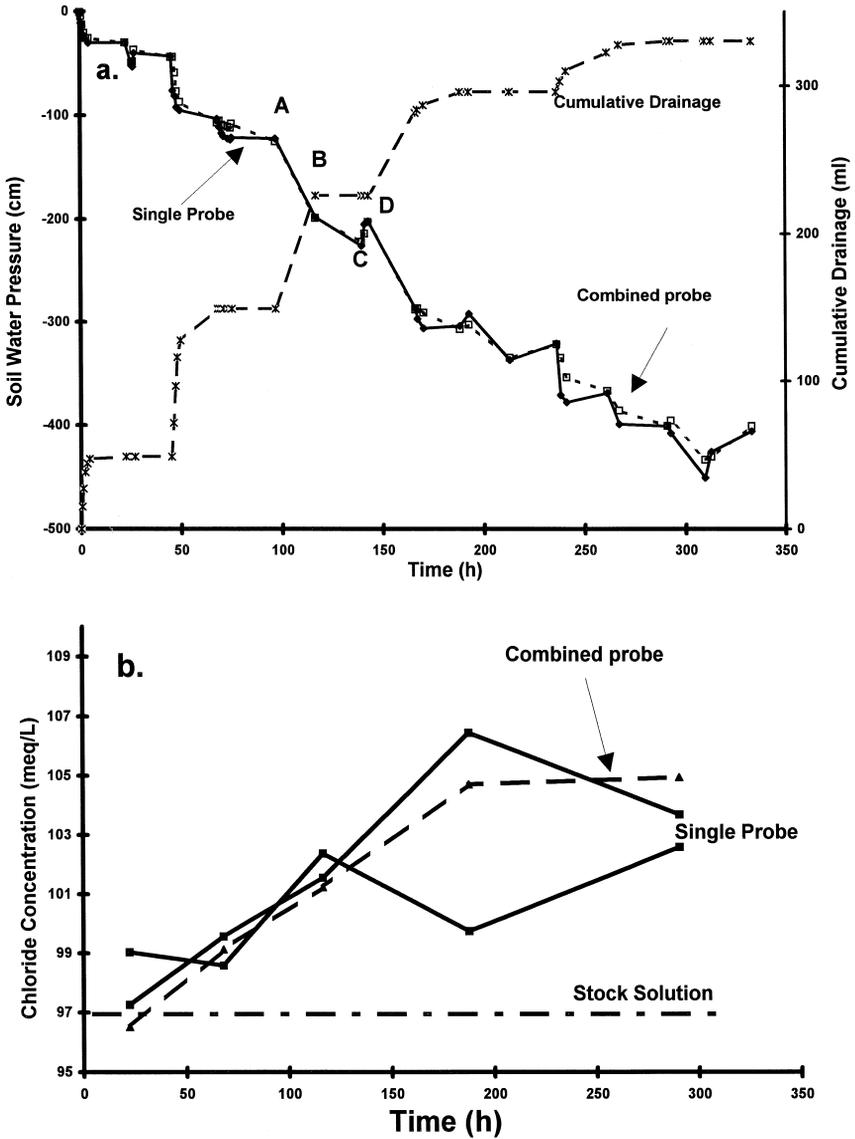


Fig. 3. (a) Soil water pressure with cumulative drainage, and (b) chloride concentration as a function of time for the Yolo soil, as determined from the conventional single probe solution sampler and the combined tensiometer–solution sampling probe.

extracted. The drainage outlet at the column bottom is closed, so that no drainage water can re-enter the soil column during the extraction period at which 250 cm vacuum is applied to the solution extraction samplers. Point C indicates the end of the extraction period at which time the SWP is -235 cm. A period of soil water redistribution and

water potential equilibration follows, until the SWP recovers back to its earlier value of -200 cm (point D). Point D also represents the start of the subsequent drainage-extraction stage where 300 cm suction is applied to the tension table of the soil column. A similar cycle occurs for each of the applied suction increments.

The cumulative drainage curve in Fig. 3a shows the increase in total drainage during those periods where suction is applied to the bottom of the column, with zero drainage during periods of solution extraction. Cumulative drainage between saturation and a soil water pressure of -400 cm corresponds to a volumetric water content decrease from 0.42 (saturated) to $0.33 \text{ cm}^3 \text{ cm}^{-3}$ for the Yolo soil.

As was the case for the Panoche and Hanford soil, soil water pressure values as measured with the conventional tensiometers were generally slightly more negative than measured with the combined sampler. Differences are attributed to the smaller contact area of the ceramic of the combined probe as compared to the ceramic cup used for the single tensiometer. A reduction in contact area reduces the soil sampling volume, represented by the tensiometric measurement. Consequently, tensiometers with larger cup size tend to measure lower soil water pressure values in heterogeneous soils. Also, Hendrickx et al. (1994) determined a similar trend, but attributed differences in soil water pressure to the effect of tensiometer cup size on response time.

3.2. Soil solution sampling

Both standard solution samplers and tension-solution sampling probes yielded adequate soil solution quantities for chemical analysis. Solutions were mostly extracted overnight over a 12–15-h period of constant vacuum. The combined tension-solution sampling probe design with a porous cup length of approximately 3.0 cm (Fig. 1) yielded in most cases less than half the volume extracted with the conventional solution samplers with a cup length of 5.4 cm. Volume differences were also observed between standard solution samplers and soil types (Table 1). In addition to the effect of sampler cup size, sampling volume differences between soils are caused by differences in hydraulic conductivity between soil types. Moreover, incomplete hydraulic contact between soils and extraction cups could lead to variability in extraction volume.

Table 1

Sampling volumes collected by conventional solution sample (single probe) and combined tensiometer-soil solution sampling probe (combined probe)

Vacuum (cm)	Yolo silt loam (ml)			Panoche loam (ml)			Hanford sandy loam (ml)		
	Single probe	Combined probe	Combined probe	Single probe	Combined probe	Combined probe	Single probe	Combined probe	Combined probe
80	9.8	7.4	2.1	6.4	5.3	3.0	8.3	9.1	1.0
150	8.1	4.0	1.0	6.0	5.2	1.0	4.9	6.1	4.5
250	6.0	4.0	2.0	6.0	4.9	2.0	6.8	9.4	11.0
350	7.0	3.0	2.0	8.0	7.3	4.0	7.8	12.8	10.0
450	7.7	5.0	2.5	8.5	7.1	3.8	4.9	6.6	5.3

The chloride concentration measured with the conventional solution samplers are compared with those determined from the combined tension–solution sampling probe in Fig. 3b. Differences in chloride concentration between the conventional solution samplers and the combined probe are generally equal to or less than the 2.0 meq l^{-1} , which is about equal to the precision of the titration instrument. The solution data of Fig. 3b also show that pore water Cl concentration tends to increase with time, as the SWP decreases.

4. Discussion

Interaction between the solution sampler and tensiometer of the combined probe can occur in two ways. First, the vacuum applied to extract soil solution may reduce the soil water pressure measured by the tensiometer compartment. This type of interaction is minimized by increasing the distance between the two compartments, and by the measurement of SWP before soil solution is extracted. Second, soil solution concentration may change because of diffusion of solutes between the soil and tensiometer compartment, or by exchange of water between the soil and tensiometer compartment through the porous ceramic. For example, the diffusion of soil solutes into the sampler is the principle of operation of the solution extractor–tensiometer sensor presented by Moutonnet et al. (1993).

Subsequent concerns with regard to potential interactions between the tensiometer and solution extraction compartments led to an improved design, which has been successfully used for field monitoring. The field-tested tension-solution probe is identical to the presented sampler, except that the length of the spacer separating the two compartments was increased. As a result, the distance between the two compartments is larger, and interactions between the solution sampler and tensiometer are minimized. The recommended separation distance of a combined field probe is approximately 10 cm. Although this distance is somewhat arbitrary, theoretical considerations indicate that the required minimum separation length is about that distance (Warrick and Amoozegar-Fard, 1977). Clearly, the influence of the applied vacuum of the solution sampler on the soil water pressure will depend on many factors, such as flow regime (steady or transient), extraction vacuum, soil hydraulic conductivity, and size and conductance of the extraction device.

Diffusion of soil solution chloride into the tensiometer compartments of the combined samplers, which were filled with deionized water, resulted in an increase of chloride concentration in the tensiometer compartments (approximate volume of cup and PVC pipe was 30 ml) in the range of $10\text{--}16 \text{ meq l}^{-1}$. Also, this type of interaction is minimized by increasing the separation distance between the two ceramic compartments.

The data in Table 2 and Fig. 3b generally show increasing Cl-concentrations as the soil water pressure decreases as caused by the larger suction increments to the tension table. Since the size of the water-filled pores decreases as the soil water pressure decreases, our data indicate that the pore water concentration is higher in the smaller solution-filled pores. Table 2 shows that the average increase in concentrations between the 450 cm and 80 cm vacuum step were 6.2, 6.5 and 3.5 meq l^{-1} for the Yolo (22.5%

Table 2

Soil solution concentration from samples collected by conventional solution sampler (single probe) and combined tensiometer–soil solution sampling probe (combined probe)

Vacuum (cm)	Yolo silt loam (meq l ⁻¹)			Panoche loam (meq l ⁻¹)			Hanford sandy loam (meq l ⁻¹)		
	Single probe		Combined probe	Single probe		Combined probe	Single Probe		Combined probe
80	97.3	99.0	96.5	99.3	97.7	97.5	98.1	96.0	95.7
150	99.6	98.6	99.1	100.9	100.0	105.0	98.4	98.5	93.6
250	101.6	102.4	101.3	104.7	102.5	102.9	99.2	100.4	95.2
350	106.4	99.8	104.7	104.7	102.5	100.9	98.6	100.4	93.5
450	103.7	102.6	105.0	107.0	105.0	102.0	102.5	103.1	94.7

clay), Panoche (20.0% clay) and Hanford (11.3% clay) soils, respectively. The increase in Cl⁻ concentration with a decrease in solution-filled pore size might be caused by anion exclusion, as the relative exclusion volume increases with decreasing soil water content. This could also explain the larger concentration increase in finer-textured soils, since anion exclusion would be most apparent for higher clay content soils, as these would potentially have a larger anion exclusion volume. Similar results were presented by Harvey (1993), who attributed the increase of bromide concentration in smaller pores to the delayed diffusion of solute from the macropores to the finer pores of the soil matrix.

5. Conclusions

An instrument capable of measuring soil water and collecting soil solution simultaneously was developed and tested in laboratory conditions for homogeneous soils. However, to minimize interactions between the two compartments of the combined probe, it is recommended to increase the distance between the compartments as compared with the presented design. Combined tension–solution sampling probes using the larger separation distance between compartments have been successfully used for in situ soil solution extraction and soil water pressure monitoring. Laboratory experiments indicated that data obtained with the combined tension–solution sampling probe were close to the conventional tensiometer and soil solution samplers. Differences in soil water pressure between the single and combined probe were attributed to differences in sampling volume of two types of probes. The increase in pore water concentration with a decrease in SWP could be attributed to anion exclusion. In either application, correct characterization of the soil water status of soils is controlled by the size of the sampling volume relative to the representative elementary volume of the soil.

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